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Chapter 7 Weather-driven Crop Models for Integrated Pest Management
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ABSTRACT ---------- 94

1. INTODUCTION ---------- 95

2. PHENOLOGY MODELS ---------- 96

3. EVAPOTRANSPIRATION MODEL AND PHENOLOGY MODEL ------ 97

4. APPLICATIONS OF PHENOLOGICAL MODELS ---------- 100

5. CONCLUSION ---------- 103

6. REFERENCES ---------- 103

摘　　要 ---------- 105

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ABSTRACT

Despite the tremendous technological advancements that have been made in recent decades, the agricultural productivity and the world food supply have been stagnated worldwide. This is partly because of the increasingly unstable weather conditions. The damages that the floods and hurricanes caused in China, Honduras and Nicaragua in1998, are unmatched for the last century and exemplifies the problem. Though natural disasters are not be avoidable, the resulting damages can be minimized if effective weather forecasting and reporting systems are developed and utilized. A case in point is the preventive measures that were taken such as adjusting the planting dates by American farmers in anticipation of a strong El Niño in early 1998, had effectively reduced the possible damages that might otherwise occur. Taiwan's agriculture is very productive and vitally important for social and political securities. It is important that weather resources and information are fully utilized to maximize the agricultural productivity and minimize the possible damages due to adverse weather conditions. This paper illustrates that phenological models, or weather driven plant and animal models, can be applied to predict crop developmental stages and the likelihood of disease breakouts. These models are powerful tools, which when effectively applied could increase the robustness and the sustainability of the agricultural production systems in Taiwan.

Key words: Weather-driven crop models, Integrated pest management.

1. INTODUCTION

Human's civilization begins with the emergence and advancement of agriculture. Agriculture evolves from the recognition of the influences of temperature and rainfall on plant growth by humans. The understanding of the impact of weather changes and patterns on the lives of plants and animals provides the basis for the development of cultivation strategies of when and where to plant what kinds of plants, which defines the adaptability and improves the productivity of agriculture. Today, climatic and live systems are still too complex to comprehend, there however does exist sufficient knowledge and technology, which if properly and timely utilized, could allow farmers to manage productive agricultural systems in most places in the world and in most times. A few well-known meteorological information systems that are designed to enhance the agricultural productivity are described below.

Application of Meteorological Information for Crop Production

The Joint Agricultural Weather Facility (JAWF) which is jointly operated by the World Agricultural Outlook Board of the U.S. Department of Agriculture (USDA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce (http://www.usda.gov/oce/waob/jawf/) porvides: (a) world crop calendar summary in maps; (b) publish the Weekly Weather and Crop Bulletin. The bulletin is published weekly on Tuesday. Includes weekly National weather and crop summaries; (c) Moisture index and drought index maps are shown for the the US daily. USDA - National Agricultural Statistics Service – also publish Crop and Weather reports on the internet. These reports include: (a) a weekly weather and crop bulletin, which contains weekly national agricultural weather summaries and the weather's effect on crops for 44 states and New England area; (b) crop developmental progress timetables, crop by crop; (c) growing and planting conditions such as top and sub-soil moisture, days suitable for fieldwork, general crop conditions, crop percents planted and harvested.

Application of Meteorological Information for Pest Management System

University of California Integrated Pest Management System (UC-IPM, http://www.ipm.ucdavis.edu) hosts one of the most comprehensive Web site of weather database and programs for agricultural pest management applications. The Web site contains information about the phenologies of more than 100 plants and pests mostly focusing on those that are important in California. Phenological models of plants

and pests that are available in the literature are generally included in the database and shown on the Web site. Each model contains the degree-day accumulations required for specific developmental stages of an organism. Most of these models have been validated in California.

Parameter-elevation Regressions on Independent Slopes Model

PRISM is an expert system that uses point data and a digital elevation model (DEM) to generate estimates of climate parameters (Daly *et al.*, 1994). Unlike other statistical weather models, PRISM includes considerations of topographical impacts on weather. PRISM is particularly suited for data interpolations at mountainous regions, because the effects of terrain on climate play a central role in the model. It is considered an expert system, because it attempts to mimic the process an expert would use to map climate parameters. The user interacts with the process through a graphical interface. PRISM has since been used to map temperature, snowfall, weather generator statistics, and others. This model can be advantages when applied to Taiwan's mountainous areas, where a lot of fruit are produced.

2. PHENOLOGY MODELS

Temperature affects living organism through its influence on the rate of metabolism. Plants and invertebrates, including insects and nematodes, require a certain amount of heat to develop from one stage of their life cycle to another. However, many organisms such as plants and pests cannot internally regulate their own temperature. These living creatures totally depend on environmental temperature for physiological developments. Because of weather variations between years, calendar dates can't be used reliably to determine the growth stages of these organisms. A good predictor for developmental stages and making management decisions is the amount of heat the organism received over time. Phenology models are models based on accumulative heat to predict time of events in an organism's development.

Two parameters are commonly used when referring to the effect of temperature on growth and development: the lower and upper threshold. The lower threshold for a species is the temperature below which development stop. The upper threshold is less well defined, but is often taken as the temperature at which the rate of growth or development begins to slow down. For many organisms the upper thresholds are not used in the model because data are lacking to obtain such estimates. Both lower and upper thresholds need to be determined through carefully controlled experiment and are unique for a specific

organism.

The amount of heat needed by an organism to develop is known as physiological time. The amount of heat required to complete a given organism's development is usually constant -- the combination of temperature (between thresholds) and time will approximately be the same. Physiological time is often expressed in units called degree-days (DD). For instance: if a species has a lower developmental threshold of 60° F, and the temperature remains at 61°F for 24 hours, one degree-day is accumulated.

Each stage of an organism's development has its own heat requirement. Development can be estimated by accumulating degree-days between temperature thresholds throughout the growing season. The accumulation of degree-days from a starting point can help predict when a developmental stage will be reached. DD monitoring does not indicate whether pest control action is warranted, but rather when a pest will reach certain susceptible life stage. Phenological models based on the cumulative DD would help to determine the risk of whether pests would be abundant.

3. EVAPOTRANSPIRATION MODEL AND PHENOLOGY MODEL

Evapotranspiration (ET) refers to the rate and amount at which water is lost from the soil and plant to the air and is an important variable to consider in estimating plant growth and making decisions about water management (Penman, 1948; Monteith, 1964; Loomis And Connor, 1992.). The water loss can occur directly from the soil, as evaporation, or via a living plant, transpiration. Transpiration is necessary since a transpiring plant is a photosynthesizing plant. Any shortage of water will decrease stomatal conductance of water, inhibit photosynthesis and thus reduce ET. By estimating the ET over the length of the growing season, the productivity of the crop and the amount of water required to produce a crop can be calculated.

ET for a crop can be measured directly, but is expensive. Instead a reference ET can be calculated based on weather variables (Allen *et al.*, 1989; Allen and Pruitt, 1991). This ET can be viewed as a potential with the actual being calculated by multiplying by a coefficient, which is specific for each crop. We have developed a program, SIMETO (Geng *at el.*, 1988, 1995), which is a weather data generator. Though the required inputs are monthly averages, SIMETO is capable of producing daily values of weather variables and reference ET values (Liang *et al.*, 1997; Snyder and Pruitt, 1994). Nine commonly

used ET estimation methods are included in SIMETO. Some of the methods are described below.

The Penman-Monteith equation (Monteith, 1964) is based on estimated net radiation (R_n) and soil heat flux (G) in MJ m^{-2}, the saturation vapor pressures at air (e_a) and dew point temperatures (e_d) in kPa, temperature (T) in °C, and wind speed (u) in m s^{-1}.

$$ET_o=[0.408\Delta(R_n-G)+\gamma(900/T+273)\ u\ (e_a-e_d)]/[\Delta+\gamma^*]$$

In the above equation, Δ is a function of T and barometric pressure, γ is the psychrometric constant, and γ^* is a modified psychrometric constant that accounts for canopy and aerodynamic resistances.

If weather variables are limited or only temperature and solar radiation data are available then an approximation method of Hargreaves (1994) can be used. That is,

$$ET_o=0.0023\ R_a\ TD^{1/2}\ (T_m+17.8)$$

In this equation, R_a is the extraterrestrial radiation, which is determined from the latitude, TD is the daily temperature range ($T_x - T_n$), T_m is the mean daily temperature ($T_m = (T_x + T_n)/2$), and T_x and T_n are the monthly averages of the daily maximum and minimum temperature.

Sometimes, pan evapotranspiration data (E_p) are available, in combination with other climate data, they can be converted to reference evapotranspiration by the following equation

$$ET_o=E_p[0.152062-0.000321u+0.002889(RH_m)+0.031886\ln(F)-0.000107(RH_m)\ln(F)]$$

where u is the wind speed in m s^{-1}, RH_m is the daily mean relative humidity in %, and F is the fetch or distance of grass around the pan in meters. This formula applies well in California conditions. Similar equations can be developed for other locations by modifying the equation coefficients.

Since both degree-day and ET models depend on temperature data, it is expected to find that there is a strong linear relationship between these model values for a given environment. Figure 1. shows the relationship between the long-term monthly temperature and Pan ET means for Taipei (1.a) and Tainan (1.b). The R^2 values are greater than 0.88 for both cases. Thus cumulative ET can be used to approximate cumulative DD in predicting plant developmental stages.

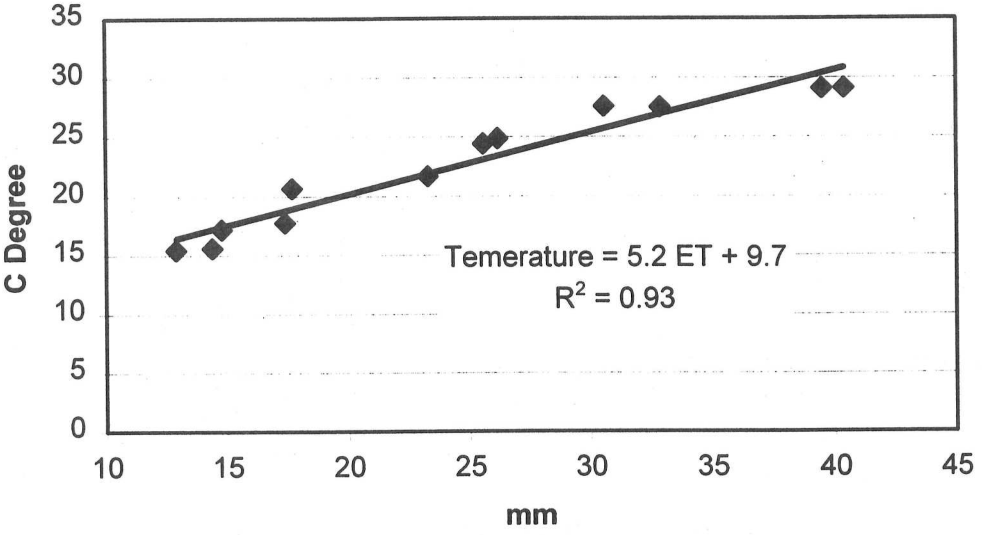

Figure 1 a. Monthly Mean Temperature and ET – Taipei

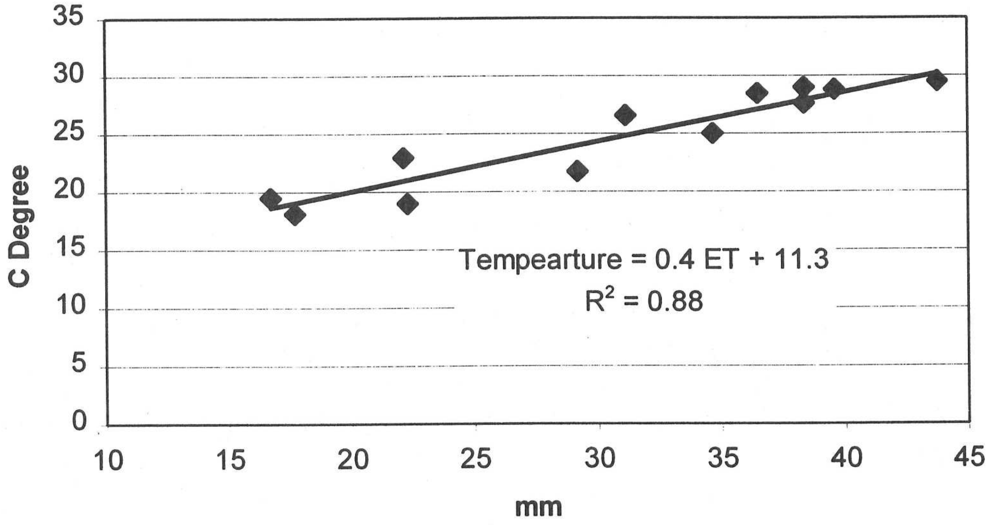

Figure 1 b. Monthly Mean Temperature and ET - Tainan

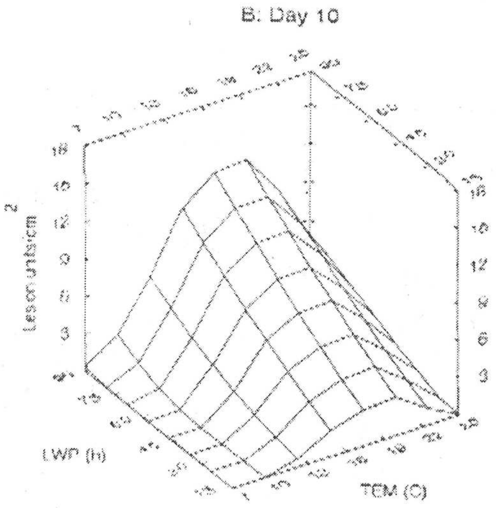

Figure 2. Lesion unit per square centimeter at day 10

4. APPLICATIONS OF PHENOLOGICAL MODELS

A Disease Model (Magboul *et al.*)

Field studies have indicated that severe outbreaks of Septoria tritici blotch of wheat are most often associated with frequent rain and high temperature during the growing season. Magboul *et al.* (1992) developed an epidemic model that can predict the severity of the disease based on forecasting temperature and moisture data. First, the observed symptoms of lesion readings on leaves over time were fitted using the logistic equation:

$$Y = \alpha_0 \ / \ (1 + \alpha_1 e^{-\alpha_2 t})$$

where Y is lesion reading cm^2 or disease severity on leaves, t is time (days) from visible symptoms, and α_0, α_1, α_2, are the coefficients of the logistic equation. The least-square estimates of these coefficients were determined by a nonlinear procedure in which the following partial derivatives were used:

$$dY/d\alpha_0 = 1 \ / \ (1 + \alpha_1 e^{-\alpha_2 t})$$
$$dY/d\alpha_1 = -\alpha_1 e^{-\alpha_2 t} \ / \ (1 + \alpha_1 e^{-\alpha_2 t})^2$$
$$dY/d\alpha_2 = \alpha_0 \alpha_1 t \ e^{-\alpha_2 t} \ / \ (1 + \alpha_1 e^{-\alpha_2 t})^2$$

The second step involved fitting the coefficients with weather variables: leaf wetness period (LWP, X_1) and temperature (TEM, X_2)

$$\alpha_i = \beta_{i0} X_0 + \beta_{i1} X_1 + \beta_{i2} X_2 + \beta_{i3} X_3 + \beta_{i4} X_4 + \beta_{i5} X_5$$

in which α_i (where i=0,1,2) is the estimated i^{th} coefficient of the disease equation, $X_0=1$, $X_1=$ LWP, X_2=TEM, $X_3=LWP^2$, $X_4=TEM^2$, X_5=LWP x TEM interaction, and β's are response function coefficients.

The final step was to develop the dynamic infection model that could predict lesion reading/cm^2 or disease severity as a function of leaf wetness period, temperature, and Time (t).

$$P = (\Sigma\, \beta_{0k}\, X_k) / \{1 + (\Sigma\, \beta_{1k}\, X_k) \quad EXP[-(\Sigma\, \beta_{2k}\, X_k)^t]\}$$

where P is the predicted lesion reading per square centimeter or disease severity and k=0 to 5. When LWP is estimated by humidity data, the above equation can be used as a phenological model to predict the severity of the disease for a given weather condition. Figure 2 shows the predicted Lesion unit per square centimeter of leaf area as a function of temperature and leaf area wetness.

A Rice Phonological Model For Taiwan

A randomized complete block with 3 blocks experiment was conducted in Hualian Crop Improvement Station (HCIS) in 1997 to collect data of rice phenology for Tainung 67. Rice was transplanted on August 13, 1997, and plant measurements were taken biweekly until rice was harvested on December 15, 1997. Plant fresh and dry weights and leave area were measured at each sampling time and yields were taken at harvest time by the breeder, Mr. Jiunn-dwu Wang of HCIS. Ms. Jen-Yu Liang of Central Weather Bureau and Mr. Wang also supplied the corresponding weather data.

Based on the weather data and the crop sampling dates, cumulative sun shin hours (CSH), cumulative radiation (CR), and heat units (HU) were calculated. The crop and weather indexes are presented in Table 1. The heat unit that is also known as degree-days (DD), is calculated based on the method described by UC- IPM program. The maximum and minimum air temperature thresholds were set respectively at 10°C and 40°C and double triangle method, horizontal cutoff were used to calculate the area under temperature curve.

The relationships of the rice plant growth and the weather units are shown in Table 1 and Figure 3. The relationships provide some ideas on modeling the plant growth as a function of weather variables. It is clear that DD, CSH, and CR are strongly linearly related. Thus any one of these variables should be adequate in constructing a rice phenology model in Taiwan. Figure 4 shows the growth of rice plant in kg per hectare per cumulative DD. A smooth cubic model fitted the data well with the R^2 equals to 0.97. In Hualian, rice matured at around 1280 DD.

Table 1. Rice Growth and Weather Data in Hualian Station (all weights are in kg ha^{-1})

Date	Leaf Area (cm^2/hill)	Fresh Weight	Fresh Weight of Tops	Dry Weight	Dry Weight of Tops	Days After Transplant	Heat Unit (degree-day)	Cum. Sun Unit (hour)	Cum. Radiation (MJ m^{-2})
8/13/97	5.2	30	0	7	0	1	18.5	3.4	11.1
8/22/97	18.2	141	0	22	0	10	183.1	23.0	82.0
9/2/97	42.7	615	0	89	0	21	372.0	67.8	183.7
9/15/97	231.7	2993	0	452	0	34	593.1	109.7	299.3
9/26/97	321.7	4904	0	852	0	45	747.7	123.6	356.8
10/9/97	701.4	8133	0	1430	0	58	929.2	135.5	411.3
10/22/97	593.8	10600	0	1919	0	71	1120.7	157.3	474.0
11/4/97	493.1	10807	1104	2422	444	84	1280.5	185.3	538.6
11/19/97	452.7	8978	1978	1815	1015	99	1447.9	263.2	638.2
12/15/97	90.3	7430	2363	1763	1570	125	1723.6	340.5	754.5

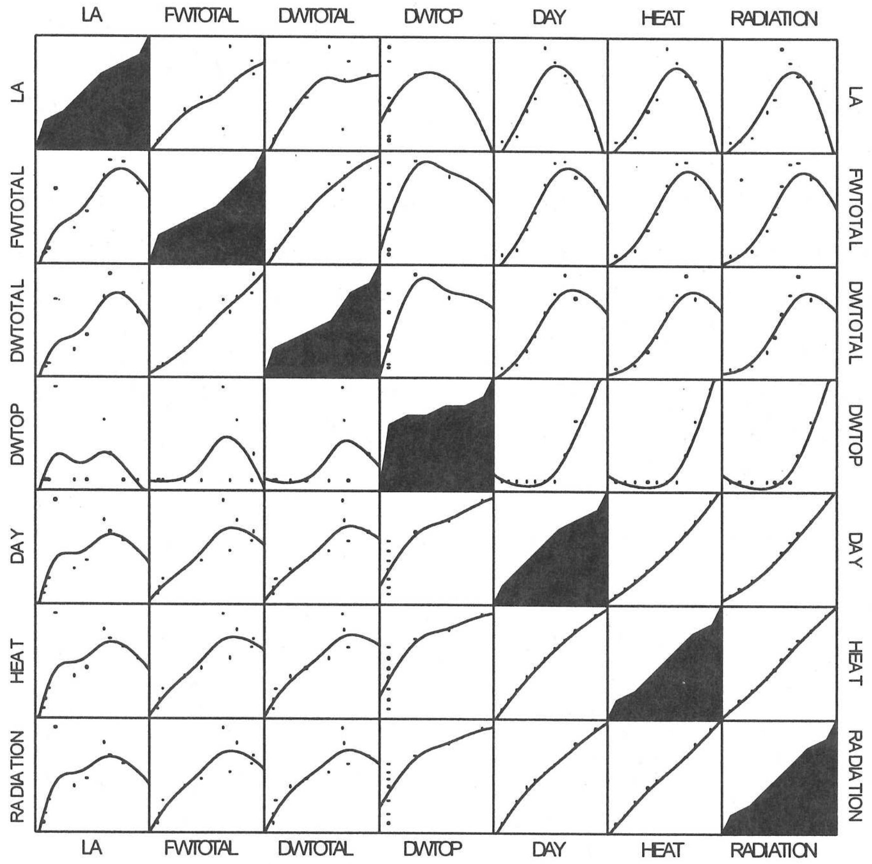

Figure 3. Relationships of Rice Phenology and Weather Parameters

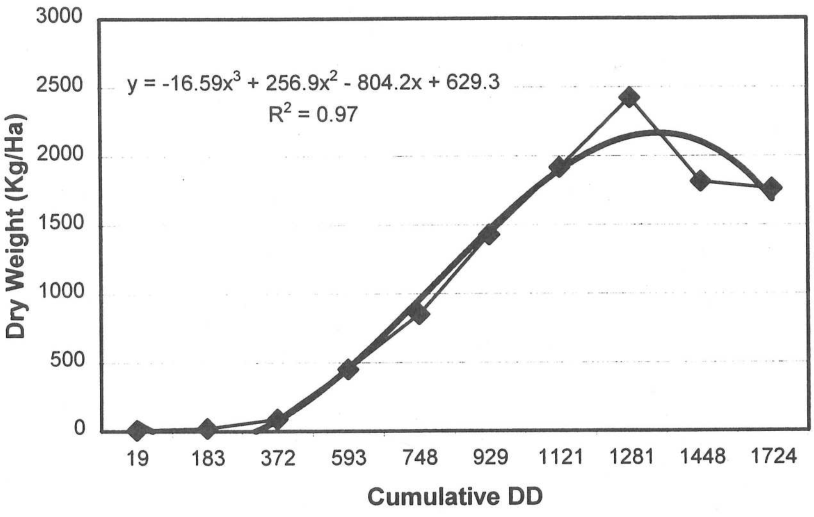

Figure 4. Rice growth (Dry Weight) as a function of Cumulative Degree Days

5. CONCLUSION

Meteorological conditions are among some of the most important factors that affect agricultural production and productivity. There are many ways the weather reports and forecasting can be used to enhance the sustainability of agricultural systems. This article introduced the approach of constructing phonological models as tools to disseminate meteorological information to either maximize the benefit of weather inputs to agriculture or to minimize the possible adverse effects. Phenological models also can be applied to predict disease breakouts so that proper measures can be taken in advance to prevent damages due to pests or disease epidemics.

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第七章　病蟲害管理之氣象-作物模式

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摘　　要

儘管近數十年來，農業技術已有驚人的進步，惟全球的農業生產和糧食的供給，卻成長緩慢；部份原因是由於不穩定之天氣型態有持續增加的趨勢。例如：1998 年大陸、宏都拉斯、尼加拉瓜所發生之洪水、颶風，遠較十九世紀者來得嚴重，此即是一明顯的例證。天然災害的發生雖無法完全地避免，但是有效的天氣預報系統若能被研發和充分加以利用的話，應可將可能發生的災害降至最低。舉例而言，在 1998 年初預測當年聖嬰現象（El Niño）顯著，美國農民依此訊息而採取調整耕種日期的因應防範措施，有效地將潛在的災害降低。台灣的農業生產豐饒，對社會和政策之安定性具有舉足輕重的影響力。因此，當前重要的課題是如何有效地利用氣候資源和天氣資訊，以增進農業生產力，並減少潛在之天然災害的發生。本文即嘗試引進生物氣候模式，修正爲適用於台灣之模式，以預測作物的生育期和病蟲害的消長情形，期望該些模式能對台灣農業生產系統的韌性和競爭力的提升有所助益。

關鍵詞：氣象-作物模式、病蟲害綜合管理。